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METHOD AND DEVICE FOR VIBRATION CONTROL

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METHOD AND DEVICE FOR VIBRATION CONTROL

This application is a continuation-in-part of U.S. Application No. 09/968,180 filed October 1, 2001 and U.S. Application No. 09/803,320 filed March 3, 2001 which claims the benefit of U.S. Application No. 09/491,969, filed January 27, 2000, which claims the benefit of U.S. Application No. 60/117,671, filed January 28, 1999, and is a continuation-in-part of U.S. Application No. 09/261,475, filed February 26, 1999, which is a continuation-in-part of U.S. Application No. 08/943,645, filed October 3, 1997, now U.S. Patent No. 6,069,433, which is a continuation of U.S. Application No. 08/188,145, filed January 27, 1994, the disclosures of each of which are hereby incorporated by reference. This application is also entitled to the benefit of Provisional Patent application No. 60/278,810.

BACKGROUND OF THE INVENTION

Tools for Fabricating Small Feature Components

In photolithography tools and other systems for fabricating electronics equipment or components, improvements in accuracy and speed are a significant advantage. Such equipment is often used in fabricating semiconductor chips, printed circuit boards, liquid crystal displays, and thin film devices, with feature sizes measured in microns and nanometers. This equipment may include multiple gantry/head assemblies, linear motors, and other equipment which produce unwanted vibrations and other movements. The present invention relates to devices and methods for reducing vibration inherent in such equipment during operation thereby to improve the speed and/or accuracy of such equipment.

Modern photolithography tools require extremely high exposure accuracy. This can only be achieved if the levels of elastic displacement at crucial points in the tool do not exceed several nano-meters. Since lithography tools contain numerous moving parts such as the reticle and wafer stages, they are subject to persistent disturbing forces acting on their structure. Moreover, the tool structure is subject to environmental disturbances such as floor vibrations and air turbulence. While the level of these disturbances can be reduced, they cannot be eliminated in their entirety.

Vibration Reducing Techniques

There are a number of existing techniques employed to limit the elastic vibration of lithography tools. For example, the stiffness of the structure that supports key elements such as the lens assembly may be increased, tuned mass dampers may be used, the signals applied to the moving stages may be shaped, or the floor vibrations may be isolated using actively controlled air springs. While effective in reducing elastic vibration, these methods often do not meet the stringent requirements of more advanced photolithography tools.

Current efforts to control vibration on precision tools may include placement of a frictional damping device called a "friction block" at the end of a gantry. This friction block serves mainly to stabilize the gantry and head trajectory control system, but it also has been shown to reduce the settling time during certain pick and place operations. However, the effectiveness of the friction block depends on precise tuning of the frictional forces. The friction block tends to wear out quickly, greatly reducing its effectiveness and contaminating the rest of the machine with particles. Moreover, the friction block works against rigid body movement, resulting in slower operation of the equipment.

Thus, improvements are desirable in the manner in which vibration is controlled in systems for fabricating electronic and other small feature components as well as the manner in which an actuator is attached to the equipment to be controlled.

SUMMARY OF THE INVENTION

Active Vibration Control

The vibration control system of the present invention provides a system for reducing vibration in a structure. The invention includes actuator elements useful for active vibration reduction, structural control, dynamic testing, precision positioning, motion sensing and control, and active damping. These actuators include electroactive materials, such as piezoelectric, electrostrictive or magnetostrictive materials. These electroactive elements may be bare or packaged electroactive elements.

In one embodiment of the invention, a vibration control system is provided comprising an actuator assembly, and a sensor for sensing a parameter of movement or performance. The vibration control system is particularly useful for controlling vibration in systems for fabricating electronics components, which often include one or more gantry assemblies, head assemblies, and/or moving stages or components. Contemplated systems for fabricating electronics components include, but are not limited to, pick and place systems, lithography systems, and those used to fabricate semiconductor chips, printed circuit boards, liquid crystal displays, and thin film devices. However, the devices and methods of the invention would be useful in fabricating systems of any sort, such as machine tool equipment, milling equipment, or systems used in an automated assembly line. Also contemplated are systems for fabricating electronic components wherein the systems comprise a lens system, a wafer stage, and a structure for supporting the lens system and wafer stage where the lens

system creates an image on the wafer stage such as would be used in modern photolithography.

In one embodiment, an active vibration control system for use with a photolithography fabricating system includes the following components: a sensor that measures the displacement levels at the key points, or provides information from which such information can be estimated; a digital or analog processor that can compute a control signal based on the sensors input, and an actuator that can induce elastic displacement in the structure.

Non-Reactive Control

In a particularly preferred embodiment, the actuator is non-reactive and does not require back support and has a very low distortion profile.

In another particularly preferred embodiment, a vibration control system in accordance with the invention comprises an induced-strain actuator that acts directly on the strain state of the structure, and has virtually no distortion. Such an actuator can excite, and therefore control, only the elastic vibration modes of the controlled structure, leaving all other vibration modes and leave the rigid body motion unaffected (such as the modes of various equipment housing structures, etc.). This contributes to the control system simplicity and robustness.

Feedback Vibration Control

In another preferred embodiment of the invention, the vibration control system further comprises a circuit in electrical communication with the actuator assembly and the sensor. In one embodiment, the sensor relays information about movement, vibration or

performance to the circuit, which, in response, signals the actuator assembly to control vibration. The vibration in the systems in which the present invention are useful may be due to external disturbance or due to the inherent disturbances generated by the system itself.

In yet another preferred embodiment of the invention, the vibration control system further comprises an electrical connection to the fabricating system. The electrical connection may provide for the fabricating system to send to, or receive from the vibration control system information such as abling or disabling signals, system status signals, or fault/error status signals. In another embodiment, a circuit according to the invention further comprises a control system comprising at least one controller. Such a control system may permit tuning of control parameters as discussed in discussed in commonly-owned U.S. Patent Application 09/896,689, gain scheduling, external gain control, or it may be a linear feed forward control, or may serve as another source of feedback control.

In an embodiment of the invention wherein the vibration control system has a control parameter tuning capability, prior to operation, the control system injects one or more test signals into the system and measures the response. The measured response is used to refine an internal model of the plant, and the control gains are modified accordingly. Control gains are kept constant while the loop is closed.

Gain Scheduling Control

In an embodiment of the invention wherein the vibration control system has a gain scheduling control, the controllers are designed for the system at several different operating points or several different desired performance profiles. In the case of a pick and place machine, these points would be different positions of the pick and place head. The controllers are stored in memory in the digital control system. During operation,

sensors feed information to the controller describing the configuration of the machine in real time. As the system moves through each operating point, the control system switches to the optimal control gains for that point. A variant of this is that the control gains used at any point in time are a linear interpolation of the gains from several controllers stored in memory for several nearby operating points.

In an embodiment of the invention wherein the vibration control system has an external gain control, the control system includes an input which connects to the computer system which monitors the overall performance of the machine. The controller implemented at any instant in time has a gain which is proportional to this signal. The monitoring system modifies this gain until optimal performance is achieved. If performance begins to move out of specification due to slow time variation, the monitoring system would repeat the gain optimization sequence.

Feed Forward

In an embodiment of the invention wherein the vibration control system has a feed forward control, in addition to the feedback control (controller driven by signals originating from sensors which monitor the structural vibration), an additional signal which is in phase with a harmonic disturbance (such as motor rotation) provided to the controller. The controller feeds forward a filtered version of this signal. The gains which adjust the magnitude and phase of the feed forward control relative to the disturbance signal may be adjusted adaptively to minimize the influence of the disturbance on the performance.

Actuators Design

In certain embodiments of the invention, the actuator assembly may comprise a strain actuator, an electroactive strain actuator, a piezoceramic strain actuator, an electroactive stack actuator, or at least two actuators. In yet another embodiment of the invention, the actuator assembly is in electrical communication with the sensor. Also in certain embodiments of the invention, the sensor may comprise a strain sensor, an accelerometer, laser displacement sensor, laser interferometer, or at least two sensors. In another embodiment of the invention, the sensor may comprise at least two sensors measuring at least two different signals. In a preferred embodiment, the sensor directly measures some aspect directly related to performance of the systems in which the present invention is useful. In a particularly preferred embodiment of the invention, the vibration control system comprises an electronic link or cable providing information about the trajectory of a gantry and head. An actuator assembly according to the present invention may include one or more strain actuation elements, such as a piezoelectric or electrostrictive plate, shell, fiber or composite; a housing forming a protective body about the element; and electrical contacts mounted in the housing and connecting to the strain element; these parts together forming a flexible card. At least one side of the assembly includes a thin sheet which is attached to a major face of the strain element, and by bonding the outside of the sheet to an object a stiff shear-free coupling is obtained between the object and the strain element in the housing.

In a preferred embodiment, the strain elements are piezoceramic plates, which are quite thin, preferably between slightly under an eighth of a millimeter to several millimeters thick, and which have a relatively large surface area, with one or both of their width and length dimensions being tens or hundreds of times greater than the thickness dimension. A metallized film makes electrode contact, while a bonding agent and insulating material hermetically seal the device against delamination, cracking and environmental exposure. The bonding agent used may be an epoxy, such as B-stage or C-stage epoxy,

a thermoplastic, or any other material useful in bonding together the piezoceramic plate, metallized film and insulating material. The specific bonding agent used will depend on the intended application of the device. In a preferred embodiment, the metallized film and insulating material are both provided in a flexible circuit of tough polymer material, which thus provides robust mechanical and electrical coupling to the enclosed elements. Alternatively, the metallized film may be located directly on the piezoceramic plate, and the insulating material may have electrical contacts.

Special PZT Package

By way of illustration, an example below describes a construction utilizing rectangular PZT plates a quarter millimeter thick, with length and width dimensions each of one to three centimeters, each element thus having an active strain-generating face one to ten square centimeters in area. The PZT plates are mounted on or between sheets of a stiff strong polymer, e.g., one half, one or two mil polyimide, which is copper clad on one or both sides and has a suitable conductive electrode pattern formed in the copper layer for contacting the PZT plates. Various spacers surround the plates, and the entire structure is bonded together with a structural polymer into a waterproof, insulated closed package, having a thickness about the same as the plate thickness, e.g., .30 to .50 millimeters. So enclosed, the package may bend, extend and flex, and undergo sharp impacts, without fracturing the fragile PZT elements which are contained within. Further, because the conductor pattern is firmly attached to the polyimide sheet, even cracking of the PZT element does not sever the electrodes, or prevent actuation over the full area of the element, or otherwise significantly degrade its performance.

The thin package forms a complete modular unit, in the form of a small "card", complete with electrodes. The package may then conveniently be attached by bonding one face to a structure so that it couples strain between the enclosed strain element and

the structure. This may be done for example, by simply attaching the package with an adhesive to establish a thin, high shear strength, coupling with the PZT plates, while adding minimal mass to the system as a whole. The plates may be actuators, which couple energy into the attached structure, or sensors which respond to strain coupled from the attached structure.

In different embodiments, particular electrode patterns are selectively formed on the sheet to either pole the PZT plates in-plane or cross-plane, and multiple layers of PZT elements may be arranged or stacked in a single card to result in bending or shear, and even specialized torsional actuation.

In accordance with a further aspect of the invention, circuit elements are formed in, or with, the vibration control system to filter, shunt, or process the signal produced by the PZT elements, to sense the mechanical environment, or even to locally perform switching or power amplification for driving the actuation elements. The actuator package may be formed with pre-shaped PZT elements, such as half-cylinders, into modular surface-mount shells suitable for attaching about a pipe, rod or shaft.

Dynamic Modeling

In a preferred embodiment of the invention special dynamic modeling techniques are utilized to investigate structural movements and to provide precise motion control.

Reticle Motion Control

In a preferred embodiment induced strain actuators are applied to elastic portions of a lithography reticle stage in order to reduce stage response to broadband vibration disturbances. Vertical positioning of the stage is accomplished using a PID controller and elastic vibration damping is implemented using a linear quadratic Gausian

controller. Reduction of elastic vibration improves positioning performance and facilitates PID control designs.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other desirable properties of the invention will be understood from the detailed description of illustrative embodiments, wherein:

FIG. 1A is a system illustration of a typical prior art actuator.

FIGS. 1B and 1C are corresponding illustrations of two systems in accordance with the present invention.

FIGS. 2A and 2B show top and cross-sectional views, respectively, of a basic actuator or sensor card in accordance with the present invention; FIG. 2C illustrates an actuator or sensor card with circuit elements.

FIG. 3 illustrates another card.

FIGS. 4A and 4B show sections through the card of FIG. 3.

FIGS. 5 and 5A show details of the layer structure of the card of FIG. 3.

FIG. 6 shows an actuator package comb electrodes for in-plane actuation.

FIG. 7 illustrates a torsional actuator package using the cards of FIG. 6.

FIGS. 8A and 8B show actuators mounted as surface mount actuators on a surface or rod, respectively.

FIG. 9 shows actuators mounted as mechanical elements.

FIG. 10 shows a block diagram of an embodiment of an electroactive vibration control system for a gantry.

FIG. 11 shows a simulated frequency response on a collect and place head at the tip of a gantry, without and with electroactive vibration control.

FIG. 12 shows the simulated time response of a collect and place head without and with electroactive control.

FIG. 13 shows extensional strain energy concentration.

FIG. 14 shows the results of a closed loop test on the frequency response of a pick and place machine having a vibration control system in accordance with the invention.

FIG. 15 shows the results of a closed loop test on the gain control of a pick and place machine having a vibration control system in accordance with the invention.

FIG. 16 shows the power spectral density of error signals recorded by a laser metrology system in a lithography machine.

FIGS. 17 through 20 show different embodiments of the invention as used with a fabricating system.

FIG. 21 shows an embodiment of the invention as used with a fabricating system.

FIG. 22 shows a simplified two-dimensional physics model of a wafer stage and wafer stage base.

FIG. 23 shows controller results.

FIG. 24 shows a block diagram for stage control.

FIG. 25 shows experimental and analytical results.

FIG. 26 shows experimental and analytical results.

FIG. 27 shows a reticle stage.

FIGS. 28A, B and C show features of a vibration control technique.

FIGS. 29A and B show results of a preferred modeling technique.

FIGS. 30A and B show response curves and other features.

FIG. 31 shows a control setup.

FIGS. 32, 33 and 34 compare results of a preferred modeling and motion control and vibration reduction techniques.

DETAILED DESCRIPTION OF THE INVENTION

Vibration Control System for Lithography Equipment

Applicants have developed a vibration control system particularly useful for controlling vibration in a system for fabricating electronics components. The vibration control system of the invention is useful for controlling vibration that is either externally produced in the system for fabricating components, or is internal to or inherent in the system. Internal vibration may be caused by various motors, such as step or D.C. motors, or hydraulic or pneumatic actuators used in a fabricating system.

A vibration control system according to the invention may comprise electroactive actuators and sensors, integrated with the fabricating system. The control and power electronics may be separate units, located adjacent to the equipment and connected to the actuators and sensors through appropriate linking cabling. Alternatively, the control and power electronics may be a fully integrated system with the fabricating system.

The electroactive actuators may be secured to or within the fabricating system in various ways. As shown in FIGS. 17, 19, and 20, for example, the actuator may be fixed into place by a bolt 414 either pushing against or going through the actuator. Alternatively, the actuator may be secured by friction, tension, or otherwise force fit. In one embodiment, as shown in FIG. 18, the actuator is bonded to a plate 412, which, in turn, is bolted to a component of a the fabricating system with bolts 414, 414', 414", and

414'''. In another embodiment, the actuator is bonded to a plate, which is bolted to a second plate, and the second plate is then bolted to a component of the fabricating component. In another embodiment, the actuator assembly is detachably secured within the vibration control system, or detachably secured to a component of a fabricating system.

First Preferred Embodiment

FIG. 21 shows a first preferred embodiment of the invention as used in a fabricating system. In this embodiment, the fabricating system comprises a wafer stage 400, a reticle stage 402, laser interferometers 404, 404', 404'', and 404''' with X&Y mirrors, and a support structure 406. The support structure 406 supports a lens assembly 410. The interferometers 404, 404', 404'', and 404''' are located on the wafer stage 400, the reticle stage 402, and on the lens assembly 410. Mounted on the support structure 406 are two actuators 408 and 408' comprising, for example, an electroactive element. Each of the actuators 408 and 408' are in electrical communication with a circuit. Signals from the interferometers 404, 404', 404'', and 404''' are relayed through an digital signal processor single board computer SBC analog I/O channel and amplifiers to the actuators 408 and 408', which, in response, controls vibration within the fabricating system. By controlling the vibration within the fabricating system, the accuracy of the placement and absolute size of the metallized traces in the semiconductor on a wafer stage may be improved. Alternatively or in addition, the through-put of the fabrication system may be increased without decreasing accuracy.

Electroactive Actuator Assemblies

Useful in this invention are electroactive actuator assemblies. FIG. 1A illustrates the process and overall arrangement of a prior art surface mounted piezoelectric actuator assembly 10. A structure 20, which may be a structural or machine element, a plate, airfoil or other interactive sheet, or a device or part thereof has a sheet 12 of smart material bonded thereto by some combination of conductive and structural polymers, 14, 16. An insulator 18, which may be formed entirely or in part of the structural polymer 16, encloses and protects the smart material, while conductive leads or surface electrodes are formed or attached by the conductive polymer. An external control system 30 provides drive signals along lines 32a, 32b to the smart material, and may receive measurement signals from surface-mounted instrumentation such as a strain gauge 35, from which it derives appropriate drive signals. Various forms of control are possible. For example, the strain gauge may be positioned to sense the excitation of a natural resonance, and the control system 30 may simply actuate the PZT element in response to a sensor output, so as to stiffen the structure, and thereby shift its resonant frequency. Alternatively, a vibration sensed by the sensor may be fed back as a processed phase-delayed driving signal to null out an evolving dynamic state, or the actuator may be driven for motion control. In better-understood mechanical systems, the controller may be programmed to recognize empirical conditions, i.e., aerodynamic states or events, and to select special control laws that specify the gain and phase of a driving signal for each actuator 12 to achieve a desired change.

For all such applications, major work is required to attach the bare PZT plate to its control circuitry and to the workpiece, and many of the assembly steps are subject to failure or, when quantitative control is desired, may require extensive modeling of the device after it has been assembled, in order to establish control parameters for a useful mode of operation that are appropriate for the specific thicknesses and mechanical stiffnesses achieved in the fabrication process. A benefit of packaging an electroactive

element when bonding to the plate is that electrical isolation or capacitive decoupling from the plate, structure or any part of the fabrication system may be achieved.

FIG. 1B shows an actuator assembly useful in one embodiment of the present invention. As shown, it is a modular pack or card 40 that simply attaches to a structure 20 with a quick setting adhesive, such as a five-minute epoxy 13, or in other configurations attaches at a point or line. The operations of sensing and control thus benefit from a more readily installable and uniformly modeled actuator structure. In particular, the modular pack 40 has the form of a card, a stiff but bendable plate, with one or more electrical connectors preferably in the form of pads located at its edge (not shown) to plug into a multi-pin socket so that it may connect to a simplified control system 50. As discussed in greater detail below with respect to FIG. 2C, the modular package 40 may also incorporate planar or low-profile circuit elements, which may include signal processing elements, such as weighting or shunting resistors, impedance matchers, filters and signal conditioning preamplifiers, and may further include switching transistors and other elements to operate under direct digital control, so that the only external electrical connections necessary are those of a microprocessor or logic controller, and a power supply.

In a further embodiment particularly applicable to some low power control situations, a modular package 60 as shown in FIG. 1C may include its own power source, such as a battery or power cell, and may include a controller, such as a microprocessor chip or programmable logic array, to operate on-board drivers and shunts, thus effecting a complete set of sensing and control operations without any external circuit connections.

The present invention specifically pertains to piezoelectric polymers, and to materials such as sintered metal zirconate, niobate crystal or similar piezoceramic materials that are stiff, yet happen to be quite brittle. It also pertains to electrostrictive materials. As used in the claims below, both piezoelectric and electrostrictive elements, in which the material of the elements has an electromechanical property, will be referred to as

electroactive elements. High stiffness is essential for efficiently transferring strain across the surface of the element to an outside structure or workpiece, typically made of metal or a hard structural polymer, and the invention in its actuator aspect does not generally contemplate soft polymer piezoelectric materials. While the terms "stiff" and "soft" are relative, it will be understood that in this context, the stiffness, as applied to an actuator, is approximately that of a metal, cured epoxy, high-tech composite, or other stiff material, with a Young's modulus greater than $.1 \times 10^6$ psi, and preferably greater than $.2 \times 10^6$ psi. When constructing sensors, instead of actuators, the invention also contemplates the use of low-stiffness piezoelectric materials, such as polyvinylidene difluoride (PVDF) film and the substitution of lower cure temperature bonding or adhesive materials. The principal construction challenges, however, arise with the first class of piezo material noted above, and these will now be described.

In general, the invention includes novel forms of actuators and methods of making such actuators, where "actuator" is understood to mean a complete and mechanically useful device which, when powered, couples force, motion or the like to an object or structure. In its broad form, the making of an actuator involves "packaging" a raw electroactive element to make it mechanically useful. By way of example, raw electroactive piezoelectric materials or "elements" are commonly available in a variety of semi-processed bulk material forms, including raw piezoelectric material in basic shapes, such as sheets, rings, washers, cylinders and plates, as well as more complex or composite forms, such as stacks, or hybrid forms that include a bulk material with a mechanical element, such as a lever. These materials or raw elements may have metal coated on one or more surfaces to act as electrical contacts, or may be non-metallized. In the discussion below, piezoelectric materials shall be discussed by way of example, and all these forms of raw materials shall be referred to as "elements", "materials", or "electroactive elements". As noted above, the invention further includes structures or devices made by these methods and operating as transducers to sense, rather than

actuate, a strain, vibration, position or other physical characteristic, so that where applicable below, the term "actuator" may include sensing transducers.

Embodiments of the invention employ these stiff electrically-actuated materials in thin sheets - discs, annuli, plates and cylinders or shells - that are below several millimeters in thickness, and illustratively about one fifth to one quarter millimeter thick. Advantageously, this thin dimension allows the achievement of high electric field strengths across a distance comparable to the thickness dimension of the plate at a relatively low overall potential difference, so that full scale piezoelectric actuation may be obtained with driving voltages of ten to fifty volts, or less. Such a thin dimension also allows the element to be attached to an object without greatly changing the structural or physical response characteristics of the object. However, in the prior art, such thin elements are fragile, and may break due to irregular stresses when handled, assembled or cured. The impact from falling even a few centimeters may fracture a piezoceramic plate, and only extremely small bending deflections are tolerated before breaking.

In accordance with the present invention, the thin electrically actuated element is encased by layers of stiff insulating material, at least one of which is a tough film which has patterned conductors on one of its surfaces, and is thinner than the element itself. A package is assembled from the piezo elements, insulating layers, and various spacers or structural fill material, such that altogether the electrodes, piezo element(s), and enclosing films or layers form a sealed card of a thickness not substantially greater than that of the bare actuating element. Where elements are placed in several layers, as will be described below, the package thickness is not appreciably greater than the sum of the thicknesses of the stacked actuating elements.

Details of Construction of Simple Actuator Card

FIG. 2A illustrates a basic embodiment 100 of the invention. A thin film 110 of a highly insulating material, such as a polyimide material, is metallized, typically copper clad, on at least one side, and forms a rectangle which is coextensive with or slightly larger than the finished actuator package. A suitable material available for use in fabricating multilayer circuit boards is distributed by the Rogers Corporation of Chandler, Arizona as their Flex-I-Mid 3000 adhesiveless circuit material, and consists of a polyimide film formed on a rolled copper foil. A range of sizes are available commercially, with the metal foils being of 18 to 70 micrometer thickness, integrally coated with a polyimide film of 13 to 50 micrometer thickness. Other thicknesses may be fabricated. In this commercial material, the foil and polymer film are directly attached without adhesives, so the metal layer may be patterned by conventional masking and etching, and multiple patterned layers may be built up into a multilayer board in a manner described more fully below, without residual adhesive weakening the assembly or causing delamination. The rolled copper foil provides high in-plane tensile strength, while the polyimide film presents a strong, tough and defect-free electrically insulating barrier.

In constructions described below, the film constitutes not only an insulator over the electrodes, but also an outer surface of the device. It is therefore required to have high dielectric strength, high shear strength, water resistance and an ability to bond to other surfaces. High thermal resistance is necessary in view of the temperature cure used in the preferred fabrication process, and is also required for some application environments. In general, polyamide/imides have been found useful, but other materials, such as polyesters or thermoplastics with similar properties, may also be used.

In the present constructions, the foil layer is patterned by conventional masking and etch techniques (for example, photoresist masking and patterning, followed by a ferric

chloride etch), to form electrodes for contacting the surface of piezo plate elements. Alternatively, a more ductile, thin conductive layer may be used. For example, a thin conductive layer may be printed on the polymer film or directly on the piezoelectric element using silver conductive ink. In FIG. 2A, electrodes 111 extend over one or more sub-regions of the interior of the rectangle, and lead to reinforced pads or lands 111a, 111b extending at the edge of the device. The electrodes are arranged in a pattern to contact a piezoelectric element along a broadly-turning path, which crosses the full length and width of the element, and thus assures that the element remains connected despite the occurrence of a few cracks or local breaks in the electrode or the piezo element. Frame members 120 are positioned about the perimeter of sheet 110, and at least one piezoelectric plate element 112 is situated in the central region so that it is contacted by the electrodes 111. The frame members serve as edge binding, so that the thin laminations do not extend to the edge, and they also function as thickness spacers for the hot-press assembly operation described further below, and as position-markers which define the location of piezo plates that are inserted during the initial stages of assembling the laminated package.

FIG. 2A is a somewhat schematic view, inasmuch as it does not show the layer structure of the device which secures it together, including a further semi-transparent top layer 116 (FIG. 2B), which in practice extends over the plate 112 and together with the spacers 120 and sheet 110 closes the assembly. A similar layer 114 is placed under the piezo element, with suitable cut-outs to allow the electrodes 111 to contact the element. Layers 114, 116 are preferably formed of a curable epoxy sheet material, which has a cured thickness equal to the thickness of the metal electrode layer, and which acts as an adhesive layer to join together the material contacting it on each side. When cured, this epoxy constitutes the structural body of the device, and stiffens the assembly, extending entirely over a substantial portion of the surface of the piezo element to strengthen the element and arrest crack growth, thereby enhancing its longevity. Furthermore, epoxy from this layer actually spreads in a microscopically thin but highly discontinuous film,

about .0025 mm thick, over the electrodes, bonding them firmly to the piezo plate, but with a sufficient number of voids and pinholes so that direct electrical contact between the electrodes and piezo elements still occurs over a substantial and distributed contact area.

FIG. 2B shows a cross-sectional view, not drawn to scale, of the embodiment of FIG. 2A. By way of rough proportions, taking the piezoelectric plate 112 as .2 - .25 millimeters in thickness, the insulating film 110 is much thinner, no more than one-tenth to one-fifth the plate thickness, and the conductive copper electrode layer 111 may have a thickness typically of ten to fifty microns, although the latter range is not a set of strict limits, but represents a useful range of electrode thicknesses that are electrically serviceable, convenient to manufacture and not so thick as to either impair the efficiency of strain transfer or introduce delamination problems. The structural epoxy 114 fills the spaces between electrodes 111 in each layer, and has approximately the same thickness as those electrodes, so that the entire assembly forms a solid block. The spacers 120 are formed of a relatively compressible material, having a low modulus of elasticity, such as a relatively uncrosslinked polymer, and, when used with a pressure-cured epoxy as described below, are preferably of a thickness roughly equivalent to the piezoceramic plate or stack of elements, so that they form an edge binding about the other components between the top and bottom layers of film 110.

A preferred method of manufacture involves applying pressure to the entire package as the layer 116 cures. The spacers 120 serve to align the piezoceramic plates and any circuit elements, as described below with reference to FIGS. 3-5, and they form a frame that is compressed slightly during assembly in the cure step, at which time it may deform to seal the edges without leaving any stress or irregularities. Compression eliminates voids and provides a dense and crack-free solid medium, while the curing heat effects a high degree of cross-linking, resulting in high strength and stiffness.

An assembly process for the embodiment of FIGS. 2A, 2B is as follows. One or more pieces of copper clad polyimide film, each approximately .025 to .050 millimeters thick in total, are cut to a size slightly larger than the ultimate actuator package dimensions. The copper side of the film is masked and patterned to form the desired shape of electrodes for contacting a piezo element together with conductive leads and any desired lands or access terminals. A pitchfork electrode pattern is shown, having three tines which are positioned to contact the center and both sides of one face of a piezo element, but in other embodiments an H- or a comb-shape is used. The patterning may be done by masking, etching and then cleaning, as is familiar from circuit board or semiconductor processing technology. The masking is effected by photoresist patterning, screening, tape masking, or other suitable process. Each of these electroded pieces of polyimide film, like a classical printed circuit board, defines the positions of circuit elements or actuator sheets, and will be referred to below simply as a "flex circuit." However, methods and devices of the invention also contemplate using an electroded piezo element, an insulator, and electrical contacts, rather than a "flex circuit".

Next, uncured sheet epoxy material having approximately the same thickness or slightly thicker than the electrode foil layer is cut, optionally with through-apertures matching the electrode pattern to allow enhanced electrical contact when assembled, and is placed over each flex circuit, so it adheres to the flex circuit and forms a planarizing layer between and around the electroded portions. The backing is then removed from the epoxy layers attached to the flex circuits, and pre-cut spacers 120 are placed in position at corner and edges of the flex circuit. The spacers outline a frame which extends above the plane of the electrodes, and defines one or more recesses into which the piezo elements are to be fitted in subsequent assembly steps. The piezo element or elements are then placed in the recesses defined by the spacers, and a second electroded film 111, 112 with its own planarizing/bonding layer 114 is placed over the element in a position to form electrode contacts for the top of the piezo element. If the device is to have

several layers of piezo elements, as would be the case for some bending actuator constructions, these assembly steps are repeated for each additional electroded film and piezoelectric plate, bearing in mind that a polyimide film which is clad and patterned on both sides may be used when forming an intermediate electrode layer that is to contact actuator elements both above and below the intermediate sheet.

Once all elements are in place, the completed sandwich assembly of patterned flex circuits, piezo sheets, spacers and curable patterned epoxy layers is placed in a press between heated platens, and is cured at an elevated temperature and pressure to harden the assembly into a stiff, crack-free actuator card. In a representative embodiment, a cure cycle of thirty minutes at 350°F and 50-100 psi pressure is used. The epoxy is selected to have a curing temperature below the depoling temperature of the piezo elements, yet achieve a high degree of stiffness.

Actuator Card Performance Characteristics

The above construction illustrates a simple actuator card having a single piezo plate sandwiched between two electroded films, so that the plate transfers shear strain efficiently through a thin film to the surface of the actuator card. The measure of transfer efficiency, given by the shear modulus divided by layer thickness squared, and referred to as gamma (Γ), depends on the moduli and thickness of the epoxy 114, the rolled foil electrodes 111, and the polyimide film 110. In a representative embodiment in which the epoxy and copper electrode layers are 1.4 mils thick and the epoxy has a modulus of $.5x10^6$, a gamma of approximately $9x10^{10}$ pounds/inch^4 is achieved. Using a thinner epoxy layer and film with .8 mil foil, substantially higher Γ is achieved. In general, the gamma of the electrode/epoxy layer is greater than $5x10^{10}$ pounds/inch^4, while that of the film is greater than $2x10^{10}$ pounds/inch^4.

It should be noted that using PZT actuator plates ten mils thick, a card having two PZT plates stacked over each other with three flex circuit electroded film layers (the middle one being double clad to contact both plates) has a total thickness of 28 mils, only forty percent greater than the plates alone. In terms of mass loading, the weight of the actuator elements represents 90% of the total weight of this assembly. Generally, the plates occupy fifty to seventy percent of the package thickness, and constitute seventy to ninety percent of its mass, in other constructions. Thus, the actuator itself allows near-theoretical performance modeling. This construction offers a high degree of versatility as well, for implementing benders (as just described) as well as stacks or arrays of single sheets.

Another useful performance index of the actuator constructed in accordance with the present invention is the high ratio of actuator strain ε to the free piezo element strain Λ, which is approximately (.8) for the two layer embodiment described herein, and in general is greater than (.5). Similarly, the ratio of package to free element curvatures, K, is approximately .85 - .90 for the described constructions, and in general is greater than .7.

Thus, overall, the packaging involved in constructing a piezo element embedded in a flex circuit impairs its weight and electromechanical operating characteristics by well under 50%, and as little as 10%, while profoundly enhancing its hardiness and mechanical operating range in other important respects. For example, while the addition of sheet packaging structure to the base element would appear to decrease attainable K, in practical use the flex card construction results in piezo bender constructions wherein much greater total deflection may be achieved, since large plate structures may be fabricated and high curvature may be repeatedly actuated, without crack failure or other mechanical failure modes arising. Several figures will illustrate the variety of constructions to which such enhanced physical characteristics are brought.

Alternative Circuit Element For Actuator Card

First, the structure of an electroactive element embedded between flex circuits not only provides a low mass unified mechanical structure with predictable response characteristics, but also allows the incorporation of circuit elements into or onto the actuator card. FIG. 2C shows a top view of one device 70 of this type, wherein regions 71, 73 each contain broad electroactive sheets, while a central region 72 contains circuit or power elements, including a battery 75, a planar power amplification or set of amplifiers 77, a microprocessor 79, and a plurality of strain gauges 78. Other circuit elements 82a, 82b may be located elsewhere along the path of circuit conductors 81 about the periphery. As with the other embodiments, spacers 120 define layout and seal edges of the device, while electrodes 111 attach the electroactive elements to the processing or control circuitry which is now built-in. The circuit elements 82a, 82b may comprise weighting resistors if the device is operated as a sensor, or shunting resistors to implement passive damping control. Alternatively, they may be filtering, amplifying, impedance matching or storage elements, such as capacitors, amplifiers or the like. In any case, these elements also are located away from electroactive plates 84. The components collectively may sense strain and implement various patterns of actuation in response to sensed conditions, or perform other sensing or control tasks.

Preferred Actuator Package

Returning now to the actuator aspect of the invention, FIG. 3 shows a top view of an actuator package 200 having dimensions of about 1.25 x 9.00 x .030 inches and assembled with two layers of piezoelectric plates of four plates each. A rectangular polyimide sheet 210 with an end tab 210a carries an electrode 211 in the form of a lattice of H-shaped thin copper lines interconnected to each other and to a single runner

211a that leads out to the tab, thus providing a low impedance connection directly to each of four rectangular regions which hold the piezo plates.

Spacer elements 220a, 220b of H-shape, or 220c of L-shape mark off corners and delineate the rectangular spaces for location of the piezo plates 216. In this embodiment, a plurality of gaps 230, discussed further below, appear between adjacent the H- or L- spacers. As will be apparent from the description below, the use of these small discrete spacer elements (I-, T- or O-shaped spacers may also be convenient) is enhanced because they may be readily placed on the tacky bonding epoxy layer 114 during assembly to mark out assembly positions and form a receiving recess for the piezo elements. However, the spacer structure is not limited to such a collection of discrete elements, but may be a single or couple of frame pieces, formed as a punched-out sheet or molded frame, to provide all, or one or more, orienting and/or sealing edges, or recesses for holding actuation of circuit components.

FIG. 5 illustrates a top view of each of the three sheet, electrode and piezo plate layers separately, while FIG. 5A illustrates the general layering sequence of the film, conductor, and spacer/piezo layers. As shown, the spacers 220 and piezo plates 216 constitute a single layer between each pair of electrode layers.

Actuator Layer Structure

FIGS. 4A and 4B (not drawn to scale) illustrate the layer structure of the assembled actuator along the vertical sections at the positions indicated by "A" and "B" in FIG. 3. As more clearly shown in FIG. 4A, a patterned bonding layer of epoxy sheet 214 is coplanar with each electrode layer 211 and fills the space between electrodes, while the spacer 220c is coplanar with the piezo plate 216 and substantially the same thickness as the plate or slightly thicker. Illustratively, the piezo plate 216 is a PZT-5A ceramic plate, available commercially in a five to twenty mil thickness, and has a continuous

conductive layer 216a covering each face for contacting the electrodes 211. The spacers 220 are formed of somewhat compressible plastic with a softening temperature of about 250°C. This allows a fair degree of conformability at the cure temperature so the spacer material may fill slight voids 214a (FIG. 4A) during the assembly process. As shown in FIG. 4B, the gaps 230 (when provided) between spacers result in openings 214b which vent excess epoxy from the curable bonding layers 214, and fill with epoxy during the cure process. As illustrated in that figure, a certain amount of epoxy also bleeds over into patches of film 215 between the electrodes 211 and the piezo plate 216. Because of the large and continuous extent of electrode 211, this patchy leakage of epoxy does not impair the electrical contact with the piezo elements, and the additional structural connection it provides helps prevent electrode delamination.

It will be appreciated that with the illustrated arrangements of electrodes, each vertically stacked pair of piezo plates may be actuated in opposition to each other to induce bending, or more numerous separate electrodes may be provided to allow different pairs of plates to be actuated in different ways. In general, as noted above, the invention contemplates even quite complex systems involving many separate elements actuated in different ways, with sensing, control, and power or damping elements all mounted on the same card. In this regard, great flexibility in adapting the card to practical tasks is further provided by its flexibility. In general, it has a supple flexibility comparable to that of an epoxy strip thirty mils thick, so that it may be bent, struck or vibrated without damage. It may also be sharply bent or curved in the region of its center line CL (FIG. 3) where no piezo elements are encased, to conform to an attaching surface or corner. The elements may be poled to change dimension in-plane or cross-plane, and the actuators may therefore be attached to transmit strain to an adjacent surface in a manner effective to perform any of the above-described control actions, or to launch particular waveforms or types of acoustic energy, such as flexural, shear or compressional waves into an adjacent surface.

Actuator With Comb-Shaped Electrodes

FIG. 6 shows another actuator embodiment 300. In this embodiment, illustrated schematically, the epoxy bonding layer, film and spacer elements are not shown, but only electrode and piezo sheets are illustrated to convey the operative mechanisms. A first set of electrodes 340 and second set 342 are both provided in the same layer, each having the shape of a comb with the two combs interdigitated so that an electrical actuation field is set up between the tooth of one comb and an adjacent tooth of the other comb. In FIG. 6, a parallel pair of combs 340a, 342a is provided on the other side of the piezo sheet, with comb electrode 340 tied to 340a, and comb electrode 342 tied to 342a, so as to set up an electric field with equipotential lines "e" extending through the piezo sheet, and in-plane potential gradient between each pair of teeth from different combs. In the embodiment shown, the piezoceramic plates are not metallized, so direct electrical contact is made between each comb and the plate. The plates are poled in-plane, by initially applying a high voltage across the combs to create a field strength above one two thousand volts per inch directed along the in-plane direction. This orients the piezo structure so that subsequent application of a potential difference across the two-comb electrodes results in in-plane (shear) actuation. Thus, the direct contact of interdigital electrodes provides to the piezo element an electrical field which is generally parallel to the actuation direction.

Use of the Actuators

In addition to shear actuation, directional actuation and damping may be effected using methods or devices of the invention. For example, as shown in FIG. 7, two such actuators 300 may be crossed to provide torsional actuation. In discussing the embodiments above, the direct transfer of strain energy through the electrode/polyimide

layer to any adjoining structure has been identified as a distinct and novel advantage. Such operation may be useful for actuation tasks or diverse as airfoil shape control actuation and noise or vibration cancellation or control. FIGS. 8A and 8B illustrates typical installations of flat (FIG. 8A) and hemicylindrical (FIG. 8B) embodiments 60 of the actuator, applied to a flat or slightly curved surface, and a shaft, respectively.

However, while the electromechanical materials of these actuators operate by strain energy conversion, applications of the present invention extend beyond strain-coupling through the actuator surface, and include numerous specialized mechanical constructions in which the motion, torque or force applied by the actuator as a whole is utilized. In each of these embodiments, the basic strip- or shell-shaped sealed actuator is employed as a robust, springy mechanical element, pinned or connected at one or more points along its length. As shown in FIGS. 9A through 9Q, when electrically actuated, the strip then functions, alone or with other elements, as a self-moving lever, flap, leaf spring, stack or bellows. In the diagrams of FIGS. 9(a) - 9(q), the elements A, A', A" . . . are strip or sheet actuators such as shown in the above FIGS., while small triangles indicate fixed or pinned positions which correspond, for example, to rigid mounting points or points of connection to a structure. Arrows indicate a direction of movement or actuation or the contact point for such actuation, while L indicates a lever attached to the actuator and S indicates a stack element or actuator.

The configurations of FIGS. 9(a)-9(c) as stacks, benders, or pinned benders may replace many conventional actuators. For example, a cantilevered beam may carry a stylus to provide highly controlled single-axis displacement to constitute a highly linear, large displacement positioning mechanism of a pen plotter. Especially interesting mechanical properties and actuation characteristics are expected from multi-element configurations 9(d) et seq., which capitalize on the actuators having a sheet extent and being mechanically robust. Thus, as shown in FIGS. 9(d) and (e), a pin-pin bellows configuration may be useful for extended and precise one-axis Z-movement positioning,

by simple face-contacting movement, for applications such as camera focusing; or may be useful for implementing a peristalsis-type pump by utilizing the movement of the entire face bearing against a fluid. As noted in connection with FIG. 3, the flex circuit is highly compliant, so hinged or folded edges may be implemented by simply folding along positions such as the centerline in FIG. 3, allowing a closed bellows assembly to be made with small number of large, multi-element actuator units. The flex circuit construction allows strips or checkerboards of actuator elements to be laid out with fold lines between each adjacent pair of elements, and the fold lines may be impressed with a thin profile by using a contoured (e.g. waffle-iron) press platen during the cure stage. With such a construction, an entire seamless bellows or other folded actuator may be made from a single flex circuit assembly.

As noted above, the piezo element need not be a stiff ceramic element, and if the flex circuit is to be used only as a sensor, then either a ceramic element, or a soft material such as PVDF may be employed. In the case of the polymer, a thinner more pliant low temperature adhesive is used for coupling the element, rather than a hard curable epoxy bonding layer. Certain embodiments of the invention are exemplified below.

Dynamic Model For Simulation and Control of Vibration

Applicants have developed techniques for modeling the effect of applying induced strain actuators to the elastic portions of a lithography stage in order to reduce broadband vibration disturbances. Vertical servo-positioning of the stage is accomplished using a PID controller, while the elastic vibration damping is implemented using a Linear Quadratic Gaussian (LQG) controller.

Applicants have also developed a numerically manageable mode based, state-space model, starting from a prior art Finite Element (FE) model. Such models typically have many tens of thousands of degrees of freedom. To achieve this, several model reduction techniques were employed, including the use of fictitious masses to simulate local

actuator effects.

An example of a stage is shown in FIG. 1. Reticle 700 is positioned on reticle stage 702. Reticle stage 702 is positioned rapidly in the verticle (z direction) with three PZT servo stacks 704A 704B and 704C. Reticle stage 704 is moveably supported by air bearing 706 which rides in the Y direction on a rail (not shown) through its center.

Model Reduction

This section describes modeling reduction techniques used for the dynamic analysis of a simulated lithography stage, resulting in state-space models for efficient simulation and augmentation of control systems. In the prior art this system was modeled with a 60,000 element FE model. This model requires extensive computer power and long time periods for typical modeling jobs.

Many such FE codes are available to solve for the structural response to a prescribed time-domain excitation by either the direct transient-response analysis or by the modal transient analysis. The direct procedure solves the equation

$$[M]\{\ddot{u}\}+[B_d]\{\dot{u}\}+[K]\{u\}=\{F(t)\} \qquad (1)$$

by numerical integration. It is very inefficient with a large number of degrees of freedom. Alternatively, a modal procedure can be used to solve

$$[M_s]\{\ddot{\xi}\}+[B_s]\{\dot{\xi}\}+[K_s]\{\xi\}=\{F_s(t)\} \qquad (2)$$

with a number of user-selected low-frequency vibration modes taken into account. The number and type of modes to be included in the modal analysis depends on the nature of the problem, with a trade off between accuracy and computational efficiency. For large structural models, the number of modes adequately taken into account is several orders of magnitudes smaller than the order of the full-size FE model. Hence, most structural dynamics analyses are based on the modal approach. One has to be careful, however, with the number and type of modes taken into account. When excitation forces are

prescribed (rather than functions of the structural response), there are usually negligible differences between the direct frequency response and the modal one, provided that the later includes all the natural vibration modes within the excitation frequency range. Hence, there is no advantage in using the direct approach in frequency-response analysis. However, when the forces are affected by the response, such as in control-augmented structures, one has to be careful in selecting the modes for modal analysis as in transient analysis.

Applicants have developed advanced modal methods that use fictitious masses and complementary static loads can be used to improve the model's accuracy and/or efficiency. As discussed later, Applicants have proved that the fictitious-mass (FM) approach is both suitable for dealing with PZT actuators, and can be applied conveniently with standard FE codes.

Derivation of State-Space Equations of Motion

For this application Applicants have derived state-space equations of motion to facilitate the integration of control systems and response simulations using modern synthesis tools, the modal equation of motion (2) is converted to the first-order state-space standard form

$$\{\dot{x}\} = [A]\{x\} + [B]\{u_i\} \qquad (3)$$

where

$$\{x\} = \begin{Bmatrix} \xi \\ \dot{\xi} \end{Bmatrix}, \qquad \{u_i\} = \{F_e\},$$
$$[A] = \begin{bmatrix} 0 & I \\ -M_s^{-1}K_s & -M_s^{-1}B_s \end{bmatrix}, \quad [B] = \begin{bmatrix} 0 \\ M_s^{-1}\phi_e^T \end{bmatrix} \qquad (4)$$

where $\{F_e\}$ is a vector of non-zero force components and $[\phi_e]$ contains the associated rows in $[\phi]$.

The outputs of the dynamic system can be expressed in the form

$$\{y\} = [C]\{x\} + [D]\{u_i\} \qquad (5)$$

where discrete displacement, velocity and acceleration outputs are cast in this form with

$$\begin{aligned}
&[C_d] = [\phi_d \quad 0], \quad [D_d] = 0 \\
&[C_v] = [0 \quad \phi_v], \quad [D_v] = 0 \\
&[C_a] = -[\phi_a][M]^{-1}[K_s \quad B_s], \\
&[D_a] = -[\phi_a][M]^{-1}[\phi_f]
\end{aligned} \qquad (6)$$

where $[\phi_d]$, $[\phi_v]$ and $[\phi_a]$ are matrices of modal displacements at the associated outputs.

The standard set of state-space equations expressed by Eqs. (3) and (5) can be used by utility codes such as Matlab for time-domain and frequency-domain analyses and for analysis and synthesis of augmenting control systems.

The Use of Fictitious Masses

A disadvantage of the modal approach is that important structural information near points of external excitation might not be contained in the low-frequency modal information. This problem might be magnified when PZT actuators are used. Adequate dynamics and control analyses with such actuators require high-accuracy representation of the surrounding structure. Static modes of structural deformations due to unit forces at the actuation points may be added to the modal basis to overcome this problem. (see Karpel, M. and Newman, M., "Accelerated Convergence for Vibration Modes Using the Substructure Coupling Method and Fictitious Coupling Masses", Israel Journal of Technology, Vol.13, 1975, pp. 55-62 and Karpel, M. and Raveh, D., "Fictitious Mass Element in Structural Dynamics", AIAA Journal, Vol. 34, No. 3, 1996, pp. 607-613. But, when the actuators are in a statically determined connection path, such as the Z-stage PZT stack-actuators, this solution might not be adequate.

The fictitious-mass (FM) modal-coupling method opened the way for the inclusion of local deformations around selected grid points. The method uses sets of low-frequency modes generated by standard normal-modes analysis procedures. Relatively large fictitious masses are added in the model at selected points when the modes are calculated. The mass effects of these masses are "cleaned" when the subsequent models are constructed, but the essential local deformations are retained in the modal information.

With a fictitious mass matrix $[M_F]$ added to the finite-element model, the resulting eigenvalues in the diagonal matrix $[\Omega_F] = \lfloor \omega_F^2 \rfloor$ and the associated eigenvectors $[\phi_F]$ satisfy

$$[K][\phi_F] = [M + M_F][\phi_F][\Omega_F] \qquad (7)$$

We now return to the original equation of motion (1) and assume that the displacement vector is a linear combination of a set of normal modes calculated with the fictitious masses, namely

$$\{u\} = [\phi_F]\{\xi_F\} \qquad (8)$$

The substitution of equation (8) in (1), the pre-multiplication by $[\phi_F]^T$ and the removal of the damping and the external force terms yield the free undamped modal equation of motion

$$\lfloor M_f - \phi^T M_F \phi \rfloor \{\ddot{\xi}_F\} + \lfloor K_f \rfloor \{\xi_F\} = \{0\} \qquad (9)$$

where $\lfloor M_f \rfloor$ and $\lfloor K_f \rfloor$ are the generalized mass and stiffness matrices associated with equation (7):

$$\begin{aligned} \lfloor M_f \rfloor &= [\phi_F]^T [M + M_F][\phi_F] \\ \lfloor K_f \rfloor &= [\phi_F]^T [K][\phi_F] \end{aligned} \qquad (10)$$

Equation (9) forms an eigenvalue problem whose eigenvalues and eigenvectors satisfy

$$\lfloor K_f \rfloor [\psi] = \lfloor M_f - \phi_F^T M_F \phi_F \rfloor [\psi][\overline{\Omega}] \qquad (11)$$

The diagonal terms of $[\overline{\Omega}]$are the "cleaned" eigenvalues, namely those obtained from the FM modes by removing the effects of the fictitious masses. In typical applications,

most eigenvalues (except the largest ones) are practically identical to those calculated directly for the original system ($[\Omega]$). The remaining eigenvalues are not natural ones, but they should be included in the model when the local response near the fictitious-mass points is of interest. The cleaned modes associate with $[\bar{\Omega}]$ can be calculated by

$$[\bar{\phi}] = [\phi_F][\psi] \qquad (12)$$

With $[\psi]$ normalized such that

$$[\psi]^T [M_f - \phi_F^T M_F \phi_F][\psi] = [I] \qquad (13)$$

A state-space model of the form of equations (3)-(6) can then be constructed with $[M_s] = [I]$, $[K_s] = [\bar{\Omega}]$ and $[\phi] = [\bar{\phi}]$.

Elastic Strain Actuators

In order to provide elastic vibration damping, elastic strain actuators were modeled on the two support arms of the lithography stage. The location of these actuators is shown in FIG. 28A below.

In this model, it was assumed that the elastic actuator stiffness values are small compared to those of the ceramic arms to which they are attached. The addition of fictitious masses to the end points of these actuators in the normal-modes analysis facilitates the accurate inclusion of actuator forces and deformations in the input and output parameters of the resulting state-space model. It also allows the addition of strain actuator stiffness effects without returning to the FE analysis. Two state-space models were generated, one based on FE normal-modes analysis without fictitious masses and one based on FE analysis with 14 fictitious masses. Six fictitious masses, 30Kg each, were added in the Z direction at the servo actuator points. Four fictitious masses, 100Kg each, were added in the X direction of the strain actuator end points. Four fictitious moments of inertia, 30Kg·m^2 each, were added in the θ_y direction at the strain actuator end points. As demonstrated below, the fictitious masses are essential for an accurate account of the strain actuator deformations.

Response to Servo Actuator Commands

The step responses shown in this section are due to a deformation command of 4μm in the Z direction at one of the servo actuators in FIG. 27, to demonstrate the main purpose of the fictitious masses, the response of the right actuator to a 4μm command at this actuator is shown in FIG. 29A and 29B (without and with fictitious masses, respectively). While the step response without fictitious masses converges to –3.74μm, the response with fictitious masses converges to -4μm, exactly as it should. Also of interest is the frequency response of the stage shown in FIGS. 30A and 30B.

Control Architecture

Applicants have developed techniques to design controllers and simulate closed loop performance. The performance requirements for the lithography tool require the pitch and roll components of the stage to be fixed while tracking a vertical (Z-motion) trajectory. For our analysis, we choose to command the three servo actuators in unison as a one degree of freedom actuator for Z-direction positioning. Since doing so reduces the ability of the actuators to attenuate the elastic vibrations of the Z-table structure, the elastic actuators located on the Z-table support arms were used to suppress the vibrations. Clearly, this is not the only possible architecture. For example, the three servo actuators could be used independently to control Z, pitch and roll motions simultaneously to a given command. However, as a first solution, the decoupled tracking and vibration damping architecture was adhered to. This architecture is attractive since the servo actuators have no control authority over the horizontal vibrations of the Z-table (Y and yaw) that are excited by Y acceleration of the reticle stage and Y-direction noise coming in through the guide. The control problem was therefore set up to allow optimal observability and controllability for the Z-direction positioning, and six degree of freedom elastic control.

There are two control loops in the design: the Z servo-positioning loop, and the vibration control loop. Both can be seen in FIG. 31 below. A PID controller is used for

the servo positioning control. A single input single output (SISO) loop is closed around an output that gives the vertical position of the stage. The input command is deducted from this output resulting in a position error signal. This signal is then fed back into a PID controller, the output of which is fed into all three positioning actuators simultaneously. The control design technique used for vibration control is multiple input multiple output (MIMO), output-weighted linear quadratic Gaussian (LQG). This technique was chosen because it is particularly effective for attenuating the response of dynamic systems in the presence of broadband stochastic disturbances such as air bearing noise. In order to simulate real-world operation, a command (either 10-micron step or 30-micron shaped input) is introduced into the servo loop, and band-limited white noise is introduced into the guide acceleration inputs. In addition, a finite-time pulse is introduced into the Y-direction guide acceleration in order to simulate stage acceleration to exposure.

Model Results

FIG. 32 shows two responses to a step input, one response with only servo control active, the other with both servo and elastic control active. FIG. 33 shows the response to the shaped input with servo control alone, while FIG. 34 shows the response to the shaped input with both servo and elastic control. The latter two figures also display the tracking error (difference of command and response.)

The use of order reduction techniques for the derivation of low-order state-space representations of critical system dynamics from large-scale finite element models has been successfully applied to a simulated lithography stage. A FE model of over 60,000 elements was reduced to a 36-state state-space model. The dynamic response of both models was compared, and the validity of the reduced-order state-space model demonstrated.

A straightforward PID design of the focusing servo was demonstrated to be difficult due to the lightly damped modes in the servo control band. Furthermore, the Z table shows considerable flexibility in the Y direction, potentially requiring unacceptably long settling times before exposure can begin after initial acceleration. A set of elastic actuators was designed to attenuate both vertical (bending, twisting), and horizontal (Y-axis) vibrations. These actuators were simulated in the FE model, and formed a subset of the inputs into the state-space model.

A set of characteristic disturbance inputs was generated, and a simple Z servo-positioning control loop designed and implemented. A fully coupled MIMO linear quadratic Gaussian compensator was designed for the vibration control loop. This compensator was shown to be very effective in reducing both vertical and horizontal plane vibrations in the stage structure. The resulting actively damped stage structure was shown by simulation to meet the servo positioning requirements even with non-optimal servo control architecture.

EXAMPLE 1: Vibration Control of a Pick and Place Machine

In this example, a vibration control system was designed to determine certain parameters of functional requirements of a gantry active control system. The functional requirements defined included (but were not limited to) the following:

- Accuracy
- Settling time
- Mass, size and location of the actuators and sensors
- Power
- Peak strains
- Lifetime
- Temperature range

- Exposure to humidity and solvents
- Cost
- Interfaces with existing gantry control system

In order to gather data on the structural response of a gantry of an automated collect and place machine during operation, the gantry was equipped with an array of piezoelectric strain sensors and accelerometers. Placement and sizing of the piezoelectric actuators required accurate strain mode shape information, which were obtained from this data, and were compared to a Finite Element Model ("FEM") of the gantry. One important piece of information obtained in this phase of the project involved the effect of different head positions on the dynamics. Both the actuator design and any control software design depended on when the vibration control was applied, i.e., while the head was moving along the gantry, and/or after it had stopped at an arbitrary position on the gantry.

Data was acquired both with and without a friction block in place, to allow at least analytical evaluation of the potential for complete replacement of the friction block by the electroactive vibration control system.

Using the data acquired above, along with finite element modeling information, the system-level design was performed. This design involved selecting a system architecture, including actuator placement, type of sensor, and the type of control algorithm. As discussed above, with the moving head having a significant effect on the gantry dynamics, the electroactive vibration control system's effectiveness was improved by making the trajectory information available in the motion control system. This information may be relayed to the motion control system with a simple clip lead attached to the proper point in the motion controller's circuitry. For example,

information such as the plots of motor current, which is often easily accessible, may be provided to the vibration control system.

After selecting the system architecture, an analytical "input/output" model of the system was developed, to design the control algorithm for vibration control, and to simulate its performance. The system design was compared to the functional requirements, to ensure compliance. This analysis served to define the specifications on the various components of the control system, especially the analog sensor signal conditioning electronics, the digital signal processor (DSP) based control unit, and the power amplifier used to provide the necessary voltage and current to the electroactive actuators.

Each of the components of the electroactive vibration control system were then designed, including the various electronic components. The electroactive actuators themselves were fabricated using methods disclosed herein. Each actuator was tested using standard quality control methods. All electronics were fabricated and tested for functionality and for compliance with the specifications devised in the system design task.

An important aspect of the design involved the integration of the actuators and sensors with the gantry. For example, for a given gantry, a 0.5 mm actuator thickness may be determined to not likely interfere with motion of the head along the gantry. The types of cable used to connect the actuators and sensor on the gantry to the electronic equipment were then determined.

In this particular example, the gantry of an automated electronics collect and place system was equipped with actuators, sensors and electronics, and analyzed using an FEM with plate elements. The basic concept, shown in block diagram in FIG. 10,

includes electroactive strain actuators and sensors bonded to the gantry, along with the necessary power, signal, and digital control electronics to achieve vibration reduction. For the purposes of this study, the head was assumed to be fixed at the end of the gantry. The installation of actuators was done using a vacuum-bonding procedure.

"Open loop" testing was then performed. Open loop testing involves injecting signals into the actuators and measuring the response of the gantry to confirm experimentally the analytical modeling done earlier in this study. This testing was performed with the gantry and head stationary, as well as moving along some "standard" trajectories. The signal(s) to be passed from the gantry and head motion controller to the vibration control system were measured as well during these tests. The electoactive actuators were distributed over 10% of the surface area of the gantry having the maximum strain energy in the first natural mode of vibration. The effectiveness of the actuator distribution at exciting the first three modes of vibration was modeled using design software. Between 80-84% of all strain energy is in the plate elements; and between 62-75% of the plates' energy is extensional strain, and therefore available for capture by electroactive control devices bonded to the surface. Thus, at least 52% of the strain energy in a mode is available. Some of this energy is in the frame/support for the moving head. As shown in FIG. 13, the extensional strain energy was sorted to maximize performance for a given amount of electroactive element.

Damping was added to the structural model. Plots of acceleration versus time at the head, after impact by a hammer, showed roughly 5% of critical damping in the first mode with the friction block in place.

Feedback control was designed using the standard Linear Quadratic Regulator (LQR) approach, ensuring that piezoelectric actuation control voltages did not exceed the actuator device limits. Actuation voltages in the closed feedback loop are proportional

to the input disturbance forces associated with the motion of the gantry. Here, the gantry was assumed to accelerate in the y-direction (transverse to the gantry axis) at a constant 25 m/s^2 until maximum velocity of 3 m/s was reached. The D'Alembert inertial force associated with a 10 kg mass was applied at the center of gravity of the head. This mass included the 5 kg head mass, plus 5 kg of effective gantry mass.

The improvements in damping and settling time were then determined after simulating the vibration-controlled system's frequency and time domain responses. Frequency responses are simulated in FIG. 11, measured at a point on the underside of the pick and place head, in the y-direction. The reduction in dynamic response to a unit input force is evident in this figure. As shown in FIG. 11, as well as Table I, mode 1 closed loop damping was about 12%, mode 2 closed loop damping was about 11%, and mode 3 closed loop damping was about 10%. Time responses at the same point, in the same direction, are simulated in FIG. 12. This simulation shows a dramatic reduction in settling time with the electroactive control. Thus, very effective control can be achieved with very little additional mass.

Table I: Gantry structural dynamic parameters.

Mode	Description	Frequency (Hz)	Inherent Damping Ratio (% of critical)	Damping Ratio with Piezo Control (%)
1	Twisting about gantry axis	46	5	12
2	Bending in xy (scanning) plane	93	5	11
3	Coupled bend/twist	136	5	10

The gantry/head structural dynamic properties, from FEM, are shown in Table I. The representative actuator distribution designed here was 0.5 mm thick, with an area of 330 cm^2, and a mass of less than 100g. The closed loop modal damping, also shown in

Table I, was at least twice the assumed 5% value inherent to the gantry with the friction block, for all three modes of vibration included in the analysis. Thus, the vibration amplitude and settling time were significantly reduced.

As shown in FIGS. 14 and 15, the vibration control system induced changes in the frequency response and gain control. In this study, the damping was increased by over one order of magnitude. This increase corresponds to an increase in placement accuracy of a factor of ten.

Following the open loop tests, the data was analyzed and the final control algorithm design was performed. If necessary, the actuator and sensor hardware may be modified to ensure compliance with the functional requirements. Then, "closed loop" testing of the final electroactive vibration control system may be performed. Closed loop testing is generally when actuators are driven at least in part by signals generated by sensors.

This study demonstrated that effective active electroactive vibration control of the gantry is possible.

EXAMPLE 2: (Vibration Control of a Lithography Machine)

A vibration control system in accordance with the invention was used in a lithography machine. As shown in FIG. 16, which shows the power spectral density of error signals recorded by a laser metrology system, use of the vibration control system resulted in a three-fold reduction in system response in the band from 75 to 125 Hz. The reduction in the peak vibration using the vibration control system would be expected to reduce the system image blur by a factor of two-three after conventional methods are used to reduce peaks at 50 Hz and 225 Hz. Alternatively, in some cases, the vibration control system might be used to reduce the peaks at 50 Hz or 225 Hz or at other levels. Reducing the image blur allows the fabrication system to produce finer trace dimensions and feature sizes and improves the accuracy of the feature placement.

An additional aspect of the invention discussed herein relates to actively stabilizing (controlling the motion of) wafer stages in lithography tools in six degrees of freedom. FIG. 22 illustrates an exemplary simplified two-dimensional physics model of a wafer stage base 501 and a wafer stage 500. This concept is readily generalizable to a real system in which three-dimensions are of concern.

The masses of the stage and the base are relatively similar and each weigh approximately 200 kg. The wafer stage base measures approximately 1m in length x 1 m in width x 0.15 m in thickness. The wafer stage measures approximately 1.25 m in length x 0.5 m in width x 0.5 m in thickness. Actuator (motor) inputs are represented by the symbol u_i, where i represents a specific voice coil motor. Alternative actuators are contemplated which include linear piezoceramic motors. Sensor outputs are represented by y_i, where i represents a laser displacement measurement that is collocated with the voice coil input. Alternative output sensors (including linear variable displacement transducers (LVDT's), accelerometers) and sensor locations (nearly co-located, sufficiently colocated) are contemplated for this example. Disturbances (represented by d_i) to the system include on-board (including motors, fans, and articulating arms) and off-board disturbances (including ground vibrations, air currents, thermal fluctuations).

The wafer stage 500 is supported on the wafer stage base by a pneumatic system 502 comprised of airbearings. This airbearing is provided to allow the wafer stage 500 to move nearly frictionless with respect to the wafer base stage 501. The wafer stage base 501 is supported on the ground by a pneumatic system of airmounts 503 and 504. The physical properties of the airmounts are represented by a spring (k1) and a dashpot (c1). The physical properties of the airbearing are represented by a spring (k2) and a dashpot (c2). The pneumatic system 503 and 504 offsets the weight of the wafer stage 500 and the wafer stage base 501 with respect to the ground. The pneumatic system 503 and 504 provides a low-frequency (approximately several Hertz) control of the plunge and tilt of the wafer stage base 501. Additional high frequency control of the base stage 501 is

provided by the voice coil motors u1, u2. A microprocessor system 510 is typically used to sense the outputs and command (actuate) the inputs as a function of the control algorithm implemented by the microprocessor system 510. The system 510 attempts to move or position the wafer stage 500 relative to the wafer stage base 501 based upon the lithography system requirements. For example the lithography system may require a constant scanning motion of the wafer stage 500 to be performed during exposure of an image on a wafer. Alternatively, the lithography system may command a rapid acceleration of the wafer stage 500 to re-locate the wafer stage to an alternative position. The wafer stage 500 would be required to make these movements to meet requirements of speed, accuracy, and/or settling time. Settling time refers to the time required to achieve a given position within some allowable variation of the absolute position. These prescribed motions with very high accelerations (up to 2g), create significant reaction forces that are transmitted to the base. In addition, these motions cause the compound center of gravity of the base stage system to rapidly change position. Currently base stabilization control is accomplished by the microprocessor system 510 through the implementation of six independent single-input, single-output (SISO) controller. Typically a SISO controller is used for each degree of freedom in the specific application. Typical three-dimensional systems could possess six degrees of freedom for each independently controlled system component or stage. SISO controllers are generally susceptible to variations in the location of the stage relative to the base. This is because the individual controller is not provided with additional output information. In one embodiment, the invention described herein, uses a multi-input, multi-output controller (MIMO) to achieve better performance than a SISO implementation even with variations of the location of the stage relative to the base. In a MIMO implementation the control is accomplished with knowledge of the output and input of more than one sensor (output) and actuator (input). Additionally, MIMO control architecture allows for the implementation of modern control techniques, including but not limited to, linear quadratic Gaussian (LQG), H-infinity, and mu

synthesis. These techniques cannot be efficiently combined with SISO architecture, because they assume knowledge of cross-axis dynamics

FIG. 23 illustrates how well a MIMO controller can follow (indicated by ACX roll moment command) a commanded input (stage pitch disturbance) to the roll moment compared with typical performance of a SISO controller (indicated by Nominal roll moment command). The MIMO controller tracks very closely to the disturbance. Thus, it is capable of reacting very quickly to a disturbance force and reject it from the system. This improves some combination of the speed, accuracy, or throughput of the stage.

In another embodiment of a stage control application in a lithography system, it was desired to decrease the settling time for a system to accurately track a commanded position. FIG. 24 illustrates the block diagram that describes the embodiment. In this embodiment, three accelerometers 600, 601, 602 are used as the sensor for feedback control. Accelerometers 600 and 601 represent accelerometers that measure x-axis acceleration. Accelerometer 602 represents a single accelerometer that measures y-axis acceleration. These measurements which are generally proportional to the acceleration are sent to a signal conditioner 606 that buffers the signals and then sends the signals which are generally proportional to the acceleration of the stage to a single board computer 607. A representative single board computer is Model SBC67 supplied by Innovative Integration Inc. with offices in Simi Valley, CA. This processor is a high performance stand-alone digital signal processor single board computer featuring analog input and output capability. The voltage signals 612 a,b,c are fed into analog inputs.

These analog inputs are then converted to digital signals that the processor then applies a control algorithm or filter to. The algorithm creates a set of digital signals which are then converted to analog output signals 613 a,b,c,d. These output signals are then applied to each of the four motors 608, 609, 610, 611. Motors 608 and 609 are x-axis motors that control the position of the stage in the x-axis. Motors 610 and 611 are y-axis motors that control the position of the stage in the y-axis. X-axis interferometer

603 and Y-axis interferometer 604 are used to measure the x and y position of the stage relative to the base of the stage (which is not depicted here for simplification).

The filter (feedback control algorithm) may be designed using the standard Linear Quadratic Regulator approach, ensuring that the motor control signals do not exceed the motor or motor amplifier limits. Motor control signals in the closed feedback loop are proportional to the accelerometer 600,601,602 signals associated with acceleration of the stage. Control design was accomplished by first creating a state-space plant model from transfer function data using the Smart ID™ system identification software package commercially available from Active Control Experts, Inc. with offices in Cambridge, Massachusetts. The filter (or controller) was then designed through computer simulation and application of techniques discussed in Fanson and *The Control Handbook, William S. Levine, Editor, CRC Press, 1996.*

FIGS. 25 and 26 represent experimental and analytical results of the MIMO control applied in this embodiment. The MIMO results are compared with results in which multiple SISO loops are instead utilized. FIG. 26 illustrates the results when zoomed in between the 0.15s and 0.30s time period. This figure illustrates that the MIMO control settles to within the settle range (approximately 100 on the y-axis of the graph) by approximately 0.19 s while the SISO (existing controller) only achieves this performance at approximately 0.26 s. This represents an improvement in settling time of approximately 30%.

The foregoing description of embodiments of the present invention are presented to demonstrate the range of constructions to which this invention applies. Those skilled in the art will appreciate that many of the modifications and variations of the invention as described herein above may be made without departing.